

Measurement of heavy-flavour production in ALICE

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Summary. — The ALICE experiment, currently in the commissioning phase, will study nucleus–nucleus and proton–proton collisions at the CERN Large Hadron Collider (LHC). We review the ALICE heavy-flavour physics program and present a selection of results on the expected performance for the case of proton–proton collisions.

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1. – Introduction

The main physics goal of the ALICE experiment [1] is the study of nucleus–nucleus collisions at the LHC, with a centre-of-mass energy per nucleon–nucleon collision $\sqrt{s_{NN}} = 5.5$ TeV for the Pb–Pb system, in order to investigate the properties of QCD matter at energy densities of up to several hundred times the density of atomic nuclei. Under these conditions a deconfined state of quarks and gluons is expected to be formed.

The measurement of open charm and open beauty production allows to investigate the mechanisms of heavy-quark production, propagation and hadronization in the hot and dense medium formed in high-energy nucleus–nucleus collisions. Heavy-quark production measurements in proton–proton collisions at the LHC energy of $\sqrt{s} = 14$ TeV, besides providing the necessary baseline for the study of medium effects in nucleus–nucleus collisions, are interesting *per se*, as a test of QCD in a new energy domain.

2. – Heavy-flavour production at LHC energies

Heavy-quark pairs ($Q\bar{Q}$) are expected to be produced in primary partonic scatterings with large virtuality $Q^2 > (2m_Q)^2$. Therefore, the baseline production cross sections in nucleon–nucleon collisions can be calculated in the framework of perturbative QCD (pQCD). For the estimate of baseline production yields in nuclear collisions, scaling of the yields with the average number of inelastic nucleon–nucleon collisions is usually assumed. The expected $c\bar{c}$ and $b\bar{b}$ production yields for pp collisions at $\sqrt{s} = 14$ TeV are 0.16 and 0.0072, respectively [2]. For the 5% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV the

expected yields are 115 and 4.6, respectively. These numbers, assumed as the baseline for ALICE simulation studies, are obtained from pQCD calculations at NLO [3], including the nuclear modification of the parton distribution functions (PDFs) [4] in the Pb nucleus (details on the choice of pQCD parameter values and PDF sets can be found in [2]). Note that the predicted yields have large uncertainties, of about a factor 2, estimated by varying the values of the calculation parameters. An illustration of the theoretical uncertainty bands for the D and B meson cross sections will be shown in sections 4 and 5, along with the expected sensitivity of the ALICE experiment.

3. – Heavy-flavour detection in ALICE

The ALICE experimental setup, described in detail in [1, 5], allows the detection of D and B mesons in the high-multiplicity environment of central Pb–Pb collisions at LHC energy, where a few thousand charged particles might be produced per unit of rapidity. The heavy-flavour capability of the ALICE detector is provided by:

- Tracking system; the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Transition Radiation Detector (TRD), embedded in a magnetic field of 0.5 T, allow track reconstruction in the pseudorapidity range $-0.9 < \eta < 0.9$ with a momentum resolution better than 2% for $p_t < 20$ GeV/c and a transverse impact parameter⁽¹⁾ resolution better than 60 μm for $p_t > 1$ GeV/c (the two innermost layers of the ITS, $r \approx 4$ and 7 cm, are equipped with silicon pixel detectors).
- Particle identification system; charged hadrons are separated via dE/dx in the TPC and via time-of-flight measurement in the Time Of Flight (TOF) detector; electrons are separated from charged hadrons in the dedicated Transition Radiation Detector (TRD), and in the TPC; muons are identified in the muon spectrometer covering the pseudo-rapidity range $-4 < \eta < -2.5$ [6].

Simulation studies [7] have shown that ALICE has good potential to carry out a rich heavy-flavour physics programme. The main analyses in preparation are:

- Open charm (section 4): fully reconstructed hadronic decays $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D_s^+ \rightarrow K^- K^+ \pi^+$ (under study), $\Lambda_c^+ \rightarrow p K^- \pi^+$ (under study) in $|\eta| < 0.9$.
- Open beauty (sections 5 and 6): inclusive single leptons $B \rightarrow e + X$ in $|\eta| < 0.9$ and $B \rightarrow \mu + X$ in $-4 < \eta < -2.5$; inclusive displaced charmonia $B \rightarrow J/\psi (\rightarrow e^+ e^-) + X$ (under study).
- Quarkonia (covered in [6]): $c\bar{c}$ (J/ψ , ψ') and $b\bar{b}$ (Υ , Υ' , Υ'') states in the e^+e^- ($|\eta| < 0.9$) and $\mu^+\mu^-$ ($-4 < \eta < -2.5$) channels.

For all simulation studies, a multiplicity $dN_{\text{ch}}/dy = 4000\text{--}6000$ was assumed for central Pb–Pb collisions. In the following, we report the results corresponding to the expected statistics collected by ALICE per LHC year: 10^7 central (0–5% σ^{inel}) Pb–Pb events at $\mathcal{L}_{\text{Pb–Pb}} = 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ and 10^9 pp events at $\mathcal{L}_{\text{pp}}^{\text{ALICE}} = 5 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$, in the barrel detectors; the forward muon arm will collect about 40 times larger samples of muon-trigger events (i.e. 4×10^8 central Pb–Pb events).

⁽¹⁾ The transverse impact parameter, d_0 , is defined as the distance of closest approach of the track to the interaction vertex, in the plane transverse to the beam direction.

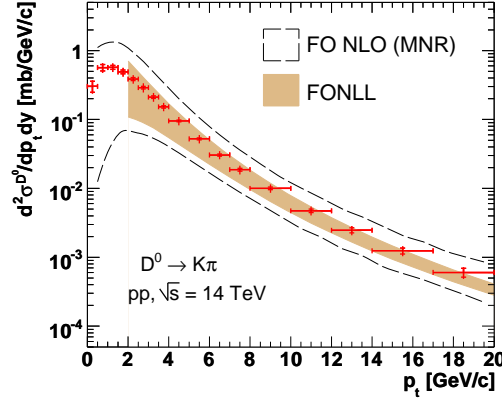


Fig. 1. – Sensitivity on $d^2\sigma^{D^0}/dp_t dy$, in pp at 14 TeV, compared to NLO pQCD predictions from the MNR [3] and FONLL [9] calculations. The inner error bars represent the statistical errors, the outer error bars represent the quadratic sum of statistical and p_t -dependent systematic errors. A normalization error of 5% is not shown.

4. – Charm reconstruction

Among the most promising channels for open charm detection are the $D^0 \rightarrow K^- \pi^+$ ($c\tau \approx 120 \mu\text{m}$, branching ratio $\approx 3.8\%$) and $D^+ \rightarrow K^- \pi^+ \pi^+$ ($c\tau \approx 300 \mu\text{m}$, branching ratio $\approx 9.2\%$) decays. The detection strategy to cope with the large combinatorial background from the underlying event is based on the selection of displaced-vertex topologies, i.e. separation from the primary vertex of the tracks from the secondary vertex and good alignment between the reconstructed D meson momentum and flight-line [7, 8]. An invariant-mass analysis is used to extract the raw signal yield, to be then corrected for detector acceptance and for selection and reconstruction efficiency. The accessible p_t range for the D^0 is 1–20 GeV/c in Pb–Pb and 0.5–20 GeV/c in pp, with statistical errors better than 15–20% at high p_t [7]. Similar capability is expected for the D^+ [8], though at present the statistical errors are estimated only in the range $1 < p_t < 8$ GeV/c. The systematic errors (acceptance and efficiency corrections, centrality selection for Pb–Pb) are expected to be smaller than 20%.

For the case of pp collisions, the experimental errors on the p_t -differential cross section are expected to be significantly smaller than the current theoretical uncertainty from perturbative QCD calculations. In Fig. 1 we superimpose the simulated ALICE measurement points for the D^0 in pp collisions to the prediction bands from the MNR fixed-order massive calculation [3] and from the FONLL fixed-order next-to-leading log calculation [9, 10]. The perturbative uncertainty bands were estimated by varying the values of the charm quark mass and of the factorization and renormalization scales. The comparison shows that ALICE will be able to perform a sensitive test of the pQCD predictions for charm production at LHC energy.

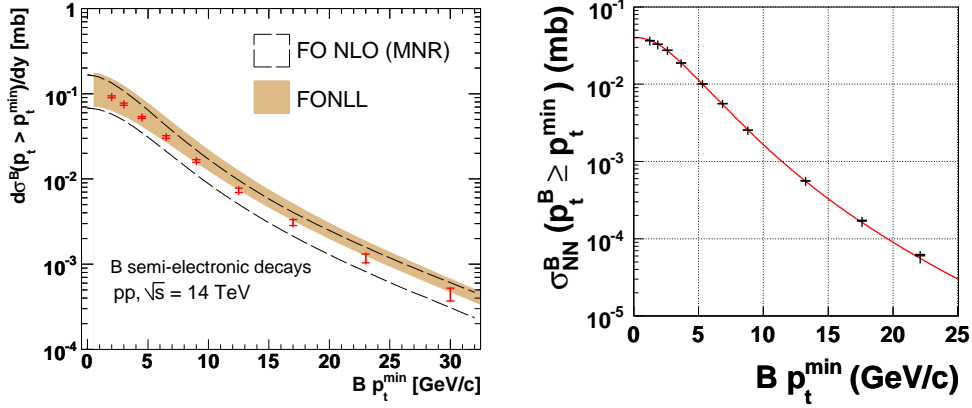


Fig. 2. – Left: sensitivity on $d\sigma^B(p_t > p_t^{\min})/dy$, in pp at 14 TeV, compared to NLO pQCD predictions from the MNR [3] and FONLL [9] calculations; error bars are defined as in Fig. 1. Right: minimum- p_t -differential production cross section per nucleon–nucleon collision for B mesons with $-4 < y < -2.5$ in central Pb–Pb collisions at 5.5 TeV, as expected to be measured from the single-muon data set. Statistical errors (represented by the thickness of the horizontal bars) corresponding to 4×10^8 events and p_t -dependent systematic errors (vertical bars) are shown. A normalization error of 10% is not shown. The line indicates the input cross section.

5. – Beauty via single electrons

The production of open beauty can be studied by detecting the semi-electronic decays of beauty hadrons, mostly B mesons. Such decays have a branching ratio of $\simeq 10\%$ (plus 10% from cascade decays $b \rightarrow c \rightarrow e$, that only populate the low- p_t region in the electron spectrum). The main sources of background electrons are: decays of D mesons; π^0 Dalitz decays and decays of light vector mesons (e.g. ρ and ω); conversions of photons in the beam pipe or in the inner detector layer and pions misidentified as electrons. Given that electrons from beauty have average impact parameter $d_0 \simeq 500 \mu\text{m}$ and a hard p_t spectrum, it is possible to obtain a high-purity sample with a strategy that relies on: electron identification with a combined dE/dx (TPC) and transition radiation (TRD) selection; impact parameter cut to reduce the charm-decay component and reject misidentified π^\pm and e^\pm from Dalitz decays and γ conversions. As an example, with $200 < d_0 < 600 \mu\text{m}$ and $p_t > 2 \text{ GeV}/c$, the expected statistics of electrons from b decays is 8×10^4 for 10^7 central Pb–Pb events, allowing the measurement of electron-level p_t -differential cross section in the range $2 < p_t < 20 \text{ GeV}/c$ with statistical errors smaller than 15% at high p_t . Similar performance figures are expected for pp collisions.

Figure 2 (left) presents the expected ALICE performance for the measurement of the p_t^{\min} -differential cross section of B mesons, $d\sigma^B(p_t > p_t^{\min})/dy$ vs. p_t^{\min} averaged in the range $|y| < 1$, which can be derived from the electron-level cross section. For illustration of the sensitivity in the comparison to pQCD calculations, we report in the same figure the predictions and the theoretical uncertainty bands from the perturbative calculations in the MNR [3] and FONLL [9, 10] approaches. It can be seen that the expected ALICE performance for 10^9 events will provide a meaningful comparison with pQCD predictions.

6. – Beauty via single muons

Beauty production can be measured also in the ALICE muon spectrometer, $-4 < \eta < -2.5$, analyzing the single-muon p_t distribution and the opposite-sign di-muons invariant mass distribution [7].

The main backgrounds to the ‘beauty muon’ signal are π^\pm , K^\pm and charm decays. The cut $p_t > 1.5$ GeV/ c is applied to all reconstructed muons in order to increase the signal-to-background ratio. Then, a fit technique allows to extract a p_t distribution of muons from B decays. A Monte Carlo procedure allows to extract B-level cross sections for the data sets (low-mass $\mu^+\mu^-$, high-mass $\mu^+\mu^-$, and p_t -binned single-muon distribution), each set covering a different B-meson $p_t > p_t^{\min}$ region. The simulation results for central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV using only the single muons are shown in Fig. 2 (right). Since only minimal cuts are applied, the reported statistical errors (represented by the thickness of the horizontal bars) are very small and the high- p_t reach is excellent. Similar performance, in terms of p_t coverage, is expected for pp collisions at $\sqrt{s} = 14$ TeV. The main sources of systematic errors (vertical bars) are: corrections for acceptance and efficiency, subtraction of the background muons from charged pion and kaon decays, and fit procedure to separate the beauty and charm components.

7. – Conclusions

We presented the expected performance of the ALICE detector for the measurement of charm and beauty production in proton–proton collisions at $\sqrt{s} = 14$ TeV. These measurements will provide sensitive tests for perturbative QCD in a new energy domain. They will also be essential for a comparison with the corresponding measurements in Pb–Pb collisions, for example for the investigation of c and b quark in-medium energy loss [11].

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